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The magnetic dipole transitions in $Xe^{129\,m}$ and Cs^{133}

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With 8 figures in the text

ABSTRACT

The half-life of the l-forbidden magnetic dipole transition in $Xe^{129\,m}$ has been measured to be $0.7 \pm 0.3 \times 10^{-9}$ s by the method of delayed coincidences and by using a multichannel time analyzer. A comparison with other transitions of the same kind shows a slight deviation for $Xe^{129\,m}$. In Cs^{133} the half life of the 80 keV $M1$ transition has been remeasured to $6.3 \pm 0.2 \times 10^{-9}$ s.

Introduction

Besides the well-known and relatively well understood regularities of $M4$ and $E2$ transitions in nuclei there is another group of isomeric states that has been found to follow certain regularities [1, 2] e.g. the l-forbidden $M1$ transitions. These are characterized by having $\Delta l = 2$, $\Delta j = 1$. From the shell model point of view such a transition in odd nuclei is forbidden, assuming that no configuration mixing exists. Only transitions involving a spin-flip are allowed. The occurrence of transitions violating this role has been explained by assuming that extraordinary terms of the magnetic dipole operator exist [3, 4], which make the matrix element of the transition different from zero. These extraordinary terms arise from some velocity-dependent interaction, e.g. spin-orbit coupling.

The experimental values obtained for the transition probability of these l-forbidden $M1$ transitions are conveniently divided into two groups [1, 2] according to as the transitions occur in nuclei with an odd number of neutrons and an even number of protons or vice versa. The transitions of the latter group occur at a rate of about five times that of the former. In the first group the known transitions are assumed to occur between the levels $d_{3/2}$ and $s_{1/2}$, which appear in nuclei in the vicinity of the shell $Z = 50$. The half-lifes of four such transitions have been measured, namely in the isotopes of Sn^{119}, $Te^{123,125}$ and Xe^{131}. In Xe^{129}, the transition $d_{3/2} \rightarrow s_{1/2}$ is known to occur, but owing to the difficulties of producing a sample of this isotope the transition probabilities have not been measured earlier.

In the following an investigation of the l-forbidden magnetic dipole transition $d_{3/2} \rightarrow s_{1/2}$ in Xe^{129}, using an electromagnetic isotope separated sample, will be described. As a byproduct of these measurements a reinvestigation of the half-life of the 80 keV level in Cs^{133} has been made.

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Experimental procedure

Xe^{129m}

Xe^{129m} is known to decay to the ground state $s_{1/2}$ by a $M4$ transition of 196 keV and a 40 keV γ-ray in cascade [5, 6, 7]. The first excited level is probably a $d_{3/2}$ state, an assumption based on a comparison with the neighbouring even-odd isotopes and shell model predictions. This is in accordance with the fact that the 40 keV γ has been identified by K/L measurement (7) to behave as a $M1$ transition.

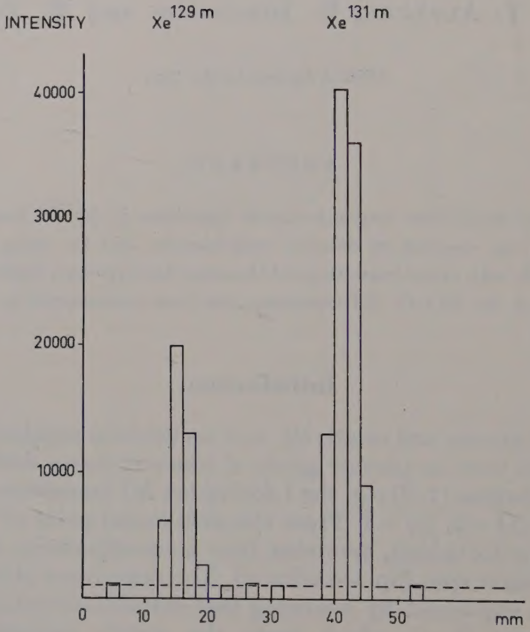

Fig. 1. Part of the mass spectrum of Xe activities obtained from an isotope separation of neutron-irradiated Xe gas, showing that the contamination between neighbouring masses is less than 0.5 %. The distribution was obtained by cutting the Al foil, on which the activity was collected, in 2 mm strips and measuring the intensity on each of these strips. The dashed line indicates the background.

In the present investigation the Xe activity has been produced in the reactor of AB Atomenergi, Stockholm, by irradiation of Xe gas. This has afterwards been electromagnetic isotope separated [8, 9] in order to obtain a sample of pure Xe^{129m}. As described earlier [5, 7] it is not possible to obtain a sample of high specific activity in this way as the stable Xe isotope 129 is populated to about 26 %. This makes the target saturated after a short separation time. It is in principle possible to reach Xe^{129m} from a reaction $Te(\alpha, 4n)Xe$, but this has not yet been tried. Fig. 1 gives the mass spectrum of the Xe activities obtained from a separation of neutron-irradiated Xe gas. The resolution was here not set to maximum, but the mass lines were defocused somewhat in order to avoid a too early saturation in the backing material. In spite of this it is seen that the contamination of neighbouring masses is smaller than 0.5 %.

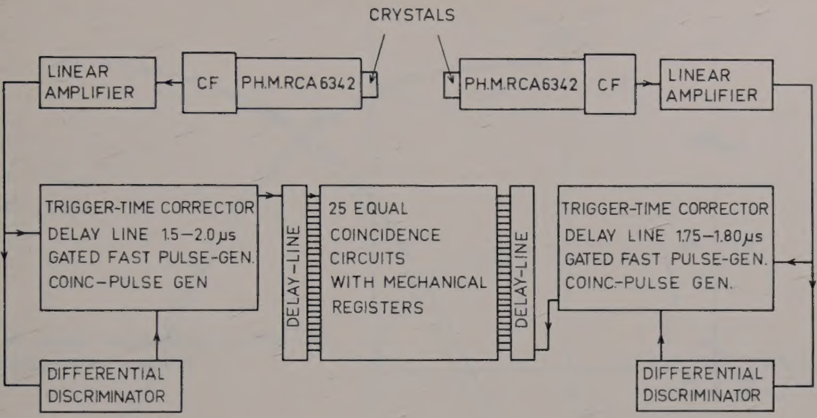

Fig. 2. Block diagram of the 25-channel time analyzer.

The half-life determination

The half-life measurement of the $d_{3/2} \rightarrow s_{1/2}$ transition has been performed by the method of delayed coincidences and using a 25-channel time analyzer [10]. Fig. 2 shows a block diagram of the instrument together with a few characteristics.

In order to obtain the best resolution of the coincidence resolution curve it is suitable to measure coincidences between electrons, as one can then use organic crystals which give a quite small time spread. In the present case, however, it was not possible to use *e–e* coincidences owing to the fact that the K-conversion electrons from the 40 keV γ had too low an energy and the L electrons were excluded by intensity considerations. The measurement has therefore utilized coincidences between the K-conversion electrons of the $M4$ transitions and X-rays of the 40 keV γ, which were detected by a NaI(Tl) crystal. As prompt coincidence curve that obtained from K-conversion electrons of the 169 keV γ-ray in Xe^{131} and the K X-ray of the same transition has been used. As the energy of the K electrons in Xe^{131} were only 27 keV smaller than those of Xe^{129m} the same setting of the instrument could be used.

When working out the result obtained in the 25-channel time analyzer it is suitable to draw an integrated delay curve as a function of the delay time rather than the intensity in each channel vs. the delay time as described in [10]. The integrated curve is in practice obtained by adding the intensity a_n in channel n to the sum of the counts of the preceding channels and plotting this as a function of time. Fig. 3 gives the result of one of several measurements of Xe^{129m} and Xe^{131m} after the above summing process has been performed. The left arms are obtained after a summing from channel 1 to 25 and the right from 25 to 1. For the case of Xe^{129m} the prompt coincidences resulting from K electrons to K X-ray have been subtracted. From the two curves it is now possible to estimate the half-life in Xe^{129m} by the usual method [11, 12], e.g. by observing the displacement of the centroid of the delayed coincidence curve with respect to the corresponding prompt curve.

However, when using the integrated coincidence curve one can obtain a value of $T_{1/2}$ by locating the point of intersection, t_n, between the two arms in the coincidence curve as follows.

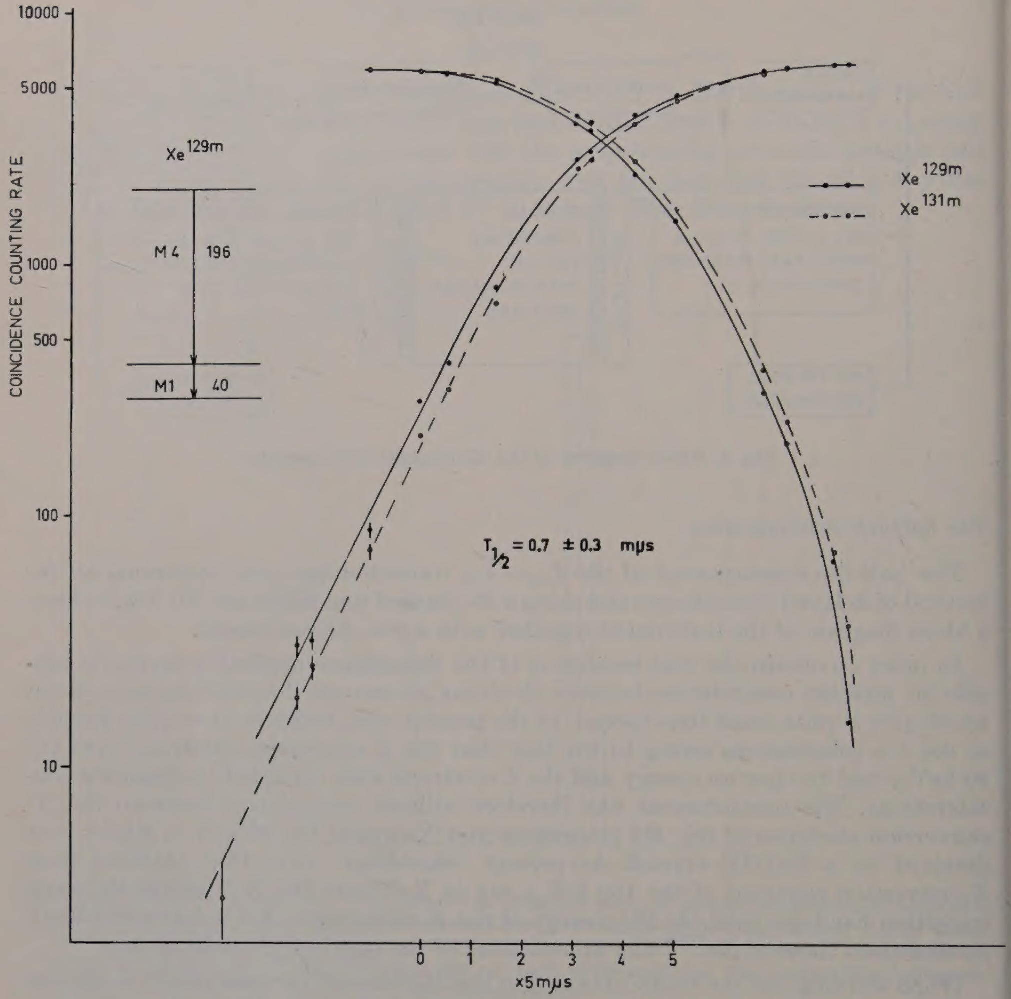

Fig. 3. Delayed coincidence curve of the 40 keV level in Xe^{129} obtained from measurement between the K-conversion electrons of the 196 keV γ-ray and X-ray of the 40 keV γ-ray. The prompt coincidences between the K-electrons of the 169 keV γ-ray–X-ray of Xe^{131m} has been used as prompt curve. For calibration of the instrument the 481 keV level ($T_{1/2} = 10.6 \pm 0.1$ mμs [21]) in Hf^{181} has been used.

In Fig. 4 a delay coincidence curve is sketched where

$$\left.\begin{aligned} F &= c[1-\exp(-\lambda t)], \quad 0 \leqslant t \leqslant \tau, \\ F &= c[1-\exp(-\lambda\tau)]\exp(-\lambda(t-\tau)), \quad \tau \leqslant t \leqslant \infty. \end{aligned}\right\} \tag{1}$$

Here c is a constant, τ a constant time spread in the measuring apparatus and λ is the decay constant to be measured. By integration of F in two ways, first between

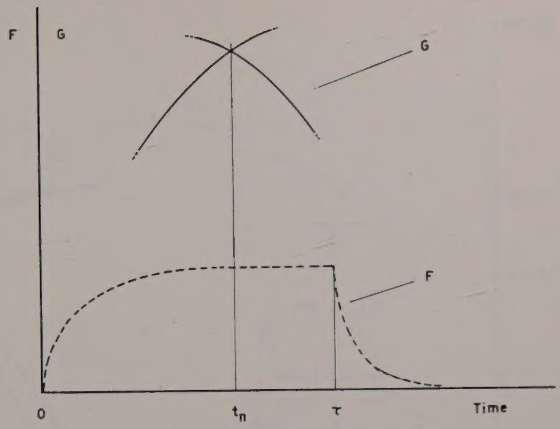

Fig. 4. A delay coincidence curve (F) and the integrated one (G).

0 to t and secondly between t and ∞ and by determining the intersection point t_n of the resultant curves one finds the following relation connecting t_n and λ

$$t_n - \frac{\tau}{2} = \frac{1}{\lambda}\left[1 - \exp\left(-\lambda t_n\right)\right] \tag{2}$$

if one assumes $t_n < \tau$.

If $\lambda t_n \gg 1$ the exponential function in (2) can be neglected and a comparison between the delayed and prompt curves gives

$$t_{n_{\text{delay}}} - t_{n_{\text{prompt}}} = \frac{1}{\lambda}\cdot \tag{3}$$

If $t_n > \tau$ one obtains the same result.

In these calculations it was assumed that the exponential time delay in the apparatus was small in comparison with the measured one. This is not the case for $\mathrm{Xe}^{129\,\mathrm{m}}$, however. By taking account of the delay in the measuring instrument it is possible to see that the following more complicated expression has to supersede (2)

$$t_n - \frac{\tau}{2} = \frac{\lambda_1}{\lambda_1 - \lambda}\cdot\frac{1}{\lambda}\left[1 - \exp\left(-\lambda t_n\right)\right] - \frac{1}{\lambda_1 - \lambda}\left[1 - \exp\left(-\lambda_1 t_n\right)\right] - \\ + \frac{1}{\lambda_1}\left[1 - \exp\left(-\lambda_1 t_n\right)\right], \tag{4}$$

where λ_1 is the decay constant of that part of the prompt curve that corresponds to the delay part in the delayed coincidence curve.

Neglecting the exponentiel functions in (4) (in the present case $\lambda_1 t_n \sim 5$), one has

$$t_n - \frac{\tau}{2} = \frac{1}{\lambda} + \frac{1}{\lambda_1}\cdot \tag{5}$$

Even in this case it is thus possible to use the relation (3).

By using the above approximation one gets the following half-life for the $M1$ transition in $\mathrm{Xe}^{129\,\mathrm{m}}$:

$$T_{1/2} = 0.7 \pm 0.3 \times 10^{-9}\ \mathrm{s}.$$

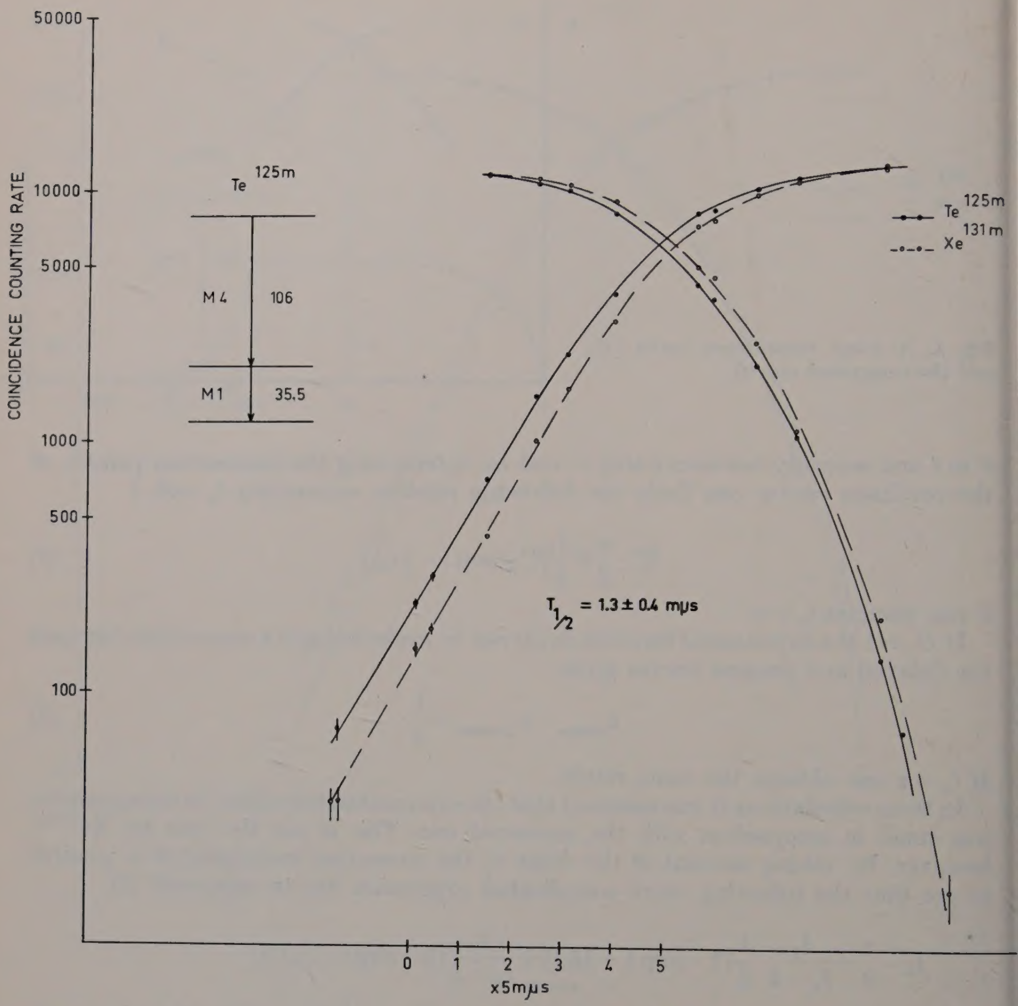

Fig. 5. Delayed coincidence curve of the 35.5 keV level of Te^{125m}. Xe^{131}, put at the same running values as Te^{125m}, has been used for the prompt coincidence curve.

By having a larger number of channels in the vicinity of the intersection one could probably get a somewhat better value. However, because of the large time spread in the NaJ crystals it should be difficult to obtain a much better estimation.

In order to check the measurements of Xe^{129m} a redetermination of the half-life of the first exited state in Te^{125} has been made. As Te^{125m} decays in the same way as Xe^{129m}, by a $M4$ transition followed by a $M1$ transition, and as the energy of the two γ-rays, 106 keV and 35.5 keV resp., is about the same as in Xe^{129m}, it is very suitable for the purpose.

Te^{125m} was obtained by isotope separation of neutron-irradiated Te. The coincidence curve was obtained by measurement between L conversion electrons of the

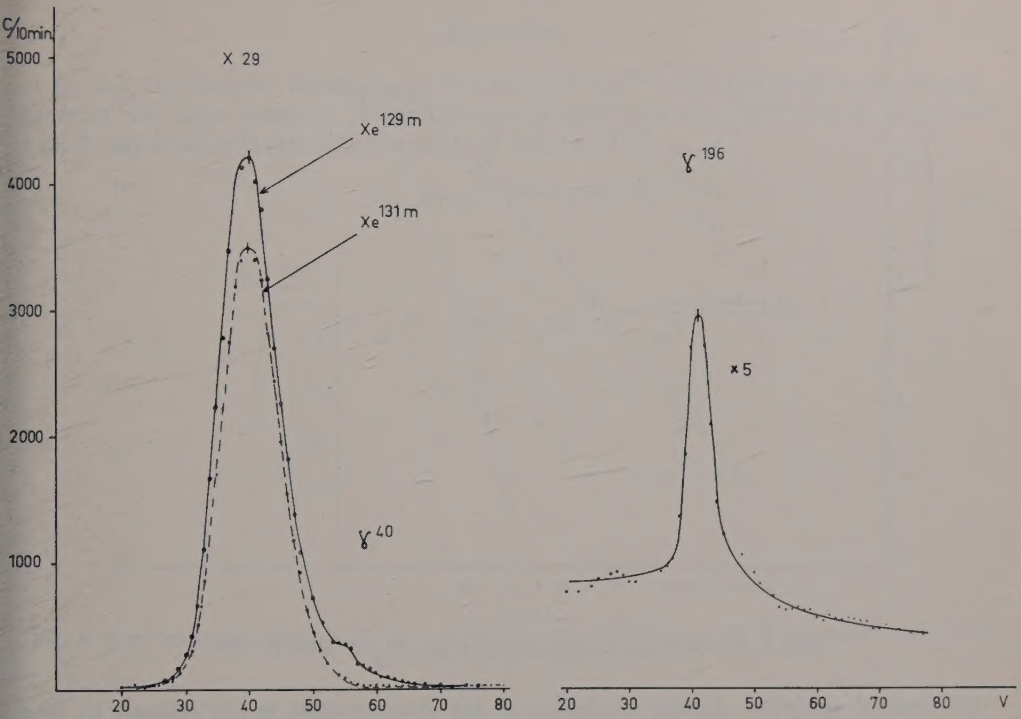

Fig. 6. Scintillation spectra of Xe^{129m} and part of Xe^{131m} (X-ray) taken with a 100-channel analyzer.

106 keV γ and K X-ray of the 35.5 keV γ. In this case, too, Xe^{131m} was used for the prompt curve and put at the same running value as Te^{125m}. From Fig. 5 one estimates the $T_{1/2} = 1.3 \pm 0.4 \times 10^{-9}$ s. This is to be compared with Graham and Bell's value of $1.58 \pm 0.15 \times 10^{-9}$ s [2].

α_K-*determination*

As mentioned above the 40 keV γ-ray in Xe^{129m} has been identified by Thulin [7] as an $M1$ transition by measurements of the K/L ratio. This has been done in two ways, one using measurements of Auger electrons and one using the intensity cascade relation. The first one gave $K/(L+M) = 6.9 \pm 2.4$, the second $K/(L+M) = 4.3 \pm 0.7$. By correcting for M conversion by using the approximation $M/L = 1/3$ one can estimate a maximal mixture of $E2$ in the transition to 40 % if the experimental results are compared to the K/L ratio given in [13]. However, from a comparison between the K/L ratio with other transitions in the same region as Xe^{129m} as in $Te^{125, 123}$ and Xe^{131} it seems probable that the larger value of $K/(L+M)$ given above is more nearly correct than the smaller one and that the mixture of $E2$ is smaller.

To investigate this further a measurement of α_K for the 40 keV γ-ray has been made by comparing the K X-ray peak and γ_{40} peak in a scintillation spectrometer. Although α_K in the actual energy region is not so sensitive for small amounts of mixture it can indeed give some information. Fig. 6 shows spectra of Xe^{129m} taken with a

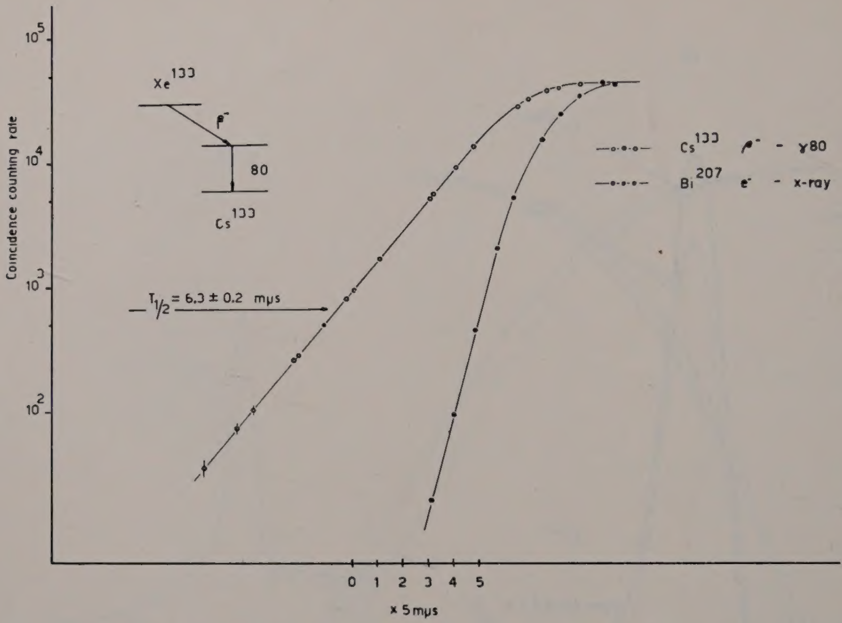

Fig. 7. Delayed coincidence curve of the 80 keV level in Cs^{133}.

100-channel analyzer. As the resolution of the spectrometer is not enough to distinguish the X-ray and 40 keV γ completely, the X-ray peak from Xe^{131m} has been used as a window curve. From the area under the 196 γ photopeak, the efficiency of the crystals at this energy, the fluorescence yield and the α_K of the $M4$ transition, it is possible to calculate the intensity of the X-ray peak due to the 196 keV γ-ray. Assuming this to be pure $M4$ one can estimate α_K for 40 keV γ from the rest of the X-ray peak and the 40 keV γ-peak:

$$\alpha_K = 7.5 \pm 2.5.$$

By compairing this with extrapolated values from the tables of Sliv [14] for $M1$ $\beta_1 = 10$ and $E2$ $\alpha_2 = 20$ it is seen that the maximum value given above for the mixture of $E2$ is probably too high.

Cs^{133}

As Xe^{133}, decaying to Cs^{133}, is produced at the same time as Xe^{129m}, the half-life of the 80 keV $M1$ transition in Cs^{133} has been remeasured, utilizing the multichannel time analyzer in order to get better stabilization and statistics than earlier measurements. Fig. 7 shows the delayed coincidence curve, which was obtained by measuring coincidences between 100 keV β and the 80 keV γ-ray. As prompt 1 MeV electrons X-ray from Bi^{207} is used. The half-life is estimated to be

$$T_{1/2} = 6.3 \pm 0.2 \times 10^{-9} \text{ s}.$$

This value is in good agreement with that reported by Graham and Bell [2], who obtained $T_{1/2} = 6.0 \pm 0.4 \times 10^{-9}$ s.

Discussion

In order to compare the $d_{3/2} \rightarrow s_{1/2}$ transition in $\mathrm{Xe}^{129\,\mathrm{m}}$ with the other known transitions of the same category in the isotopes of Sn^{119} [15, 16], Te^{123} [15, 2, 17], Te^{125} [15, 2, 17] and Xe^{131} [15, 18], the value of (cf. e.g. [19])

$$\log_{10}\{\tau A^{(2\Delta I-2)/3} E^{2\Delta I+1}\} \tag{6}$$

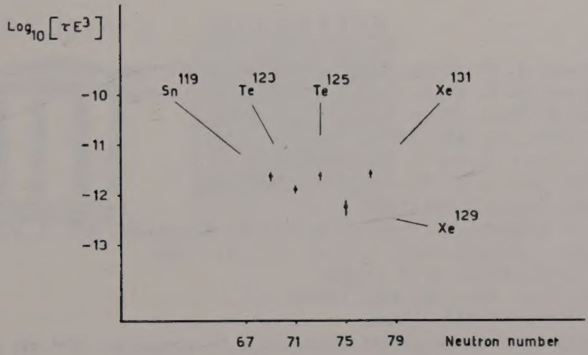

Fig. 8. The "reduced" lifetime of the l-forbidden $M1$ transition in Xe^{129} compared with those in Xe^{131}, $\mathrm{Te}^{123,\,125}$ and Sn^{119}.

the $\log_{10}$ of the "reduced" life-time has been plotted in Fig. 8 as a function of the neutron number in the five known isotopes. The mean life τ is calculated in the usual way.

$$\tau = 1.44\,(1+\alpha_{\mathrm{tot}})\left(1+\frac{E2}{M1}\right)T_{1/2} \tag{7}$$

where $E2/M1$ gives the quotient between the amount of $E2$ and $M1$ in the actual transition. $E2/M1$ has only been measured accurately in the isotopes of Te [17]. In the other isotopes an estimation is obtained from α_K and K/L. In $\mathrm{Xe}^{129\,\mathrm{m}}$ the maximum mixture of $E2$ is assumed to be 25 %. This is incorporated in the error of the "reduced" life-time.

As seen in Fig. 8 the point for $\mathrm{Xe}^{129\,\mathrm{m}}$ shows a small deviation from the other four transitions, which seem to be rather constant, as has been pointed out several times earlier [1, 2]. Owing to the large uncertainties in the experimentally determined value of α_K and K/L and due to the fact that the theoretical value for these constants is not quite fixed as all effects from the "finite size" of the nuclei are not yet taken into account [20], the estimation of the $E2$ mixture can be larger than that assumed above, but this does not seem to be probable.

It would therefore be possible to discern a certain tendency for the value of the reduced lifetime to increase with neutron number for a fixed proton number as in Te and Xe. However, there are probably still too few transitions of the type $d_{3/2} \rightarrow s_{1/2}$ known and too large uncertainties in these to make it possible to estimate any fine structure of the empirical matrix element as a function of Z and N.

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REFERENCES

1. M. Goldhaber and A. W. Sunyar, Phys. Rev. *83*, 906 (1951).
2. R. L. Graham and R. E. Bell, Can. J. Phys. *31*, 377 (1953).
3. R. G. Sack and M. Ross, Phys. Rev. *84*, 379 (1951).
4. M. Ross, Phys. Rev. *88*, 935 (1952).
5. I. Bergström, Ark. f. Fysik *5*, 263 (1952).
6. C. T. Borkowski and A. R. Brosi, ORNL 607, 52.
7. S. Thulin, Ark. f. Fysik *7*, 269 (1953).
8. I. Bergström, S. Thulin, N. Svartholm, and K. Siegbahn, Ark. f. Fysik *1*, 1949.
9. T. Alväger and J. Uhler, Ark. f. Fysik *13*, 145, 1958.
10. B. Johansson, Nucl. Instr. *2*, 61 (1958).
11. T. D. Newton, Phys. Rev. *78*, 490 (1950).
12. Z. Boy, Phys. Rev. *77*, 419 (1950).
13. M. E. Rose, Chapter 14 in Beta- and Gamma-ray Spectroscopy (Ed. K. Siegbahn), North-Holland Publ. Co., Amsterdam, 1955.
14. L. A. Sliv and I. M. Band, published by Academy of Sciences of the U.S.S.R., Moscow–Leningrad, 1956.
15. J. M. Hollander, I. Perlman, and G. T. Seaborg, Rev. Mod. Phys. *25*, 469 (1953).
16. J. L. Olsen, L. G. Mann, and M. Lindner, Bull. Am Phys. Soc. *1*, 41 (1956).
17. N. Goldberg and S. Frankel, Phys. Rev. *100*, 1350 (1955).
18. R. E. Bell, R. L. Graham, and H. E. Petch, Can. J. Phys. *30*, 35 (1952).
19. M. Goldhaber and A. W. Sunyar, Chapter 16 in Beta- and Gamma-Ray Spectroscopy (Ed. K. Siegbahn).
20. M. E. Rose, Proceedings of the Rehovoth Conference on Nuclear Structure, p. 263, 1958.
21. B. Johansson, J. Blomqvist, to be published.

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